Integration of Water Quantity and Quality in Strategic River Basin Planning

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Abstract: The integration of surface water quantity and quality objectives within the framework of a decision-support tool is presented in an application to the 12,400-km^2 Piracicaba River Basin in the state of Sao Paulo, Brazil. Emphasis is given to simulation-based assessment of strategic planning alternatives through the combined use of water allocation (MODSIM) and water quality routing (QUAL2E-UNCAS) models. Uncertainty from temporal and spatial variability and inadequate data associated with model parameters is addressed. Performance measures for water allocation include total reliability, total vulnerability, and total resiliency. Water quality performance measures are stream standard compliance reliability, water quality index, spatial uniformity of water quality, and temporal uniformity of water quality. These measures are used to evaluate and compare alternatives in light of multiple planning objectives. Six management alternatives, combining various reservoir release policies with differing levels of wastewater treatment, are refined through systematic simulation to a final plan recommended for detailed consideration. The recommended plan results in predicted performance that dependably meets transbasin diversion to the city of Sao Paulo while maintaining high intrabasin water allocation performance.

INTRODUCTION

In effective water management, concern must be shown not only for the total amounts of water needed to meet diverse demands but also for the properties that make it fit for multiple and cyclical uses. Historically, a distinct separation in the consideration of water quantity and water quality concerns has existed, with most of the attention given to the provision of required quantities. However, over the last two decades, water quality has gained progressively more attention, reaching its current status as one of the most studied and discussed subjects in the water resources field. Water quality characteristics of major concern include biochemical oxygen demand (BOD) and its complementary effect on total dissolved oxygen (DO), total dissolved solids, specific chemical species (e.g., nitrogen and phosphorus), pathogenic organisms and their indicators, toxic elements (e.g., heavy metals and radionuclides), temperature, pH, and sediment load. These constituents have triggered keen interest among policymakers who have increasingly revised institutional, regulatory, and operational frameworks to address water quality at the river basin scale.

Issues of water allocation also are becoming more unwieldy. The expanding need for water is driven by population growth and urban development, by demand for the increased agricultural productivity derived from expanded irrigation, and by the degradation of existing supplies (World Bank 1993). The emergence of contemporary water uses such as wildlife preservation, habitat enhancement, and recreational requirements also has added to the complexity of the demand problem. According to Nunn (1987), the United States and many other countries have shifted from young water economies with a focus on developing new water supplies to mature economies with a focus on conserving and reallocating present supplies. ‘‘This maturing water economy has resulted in greater competition between water users and more complex problems for water managers.’’ Competition among different economic sectors (agricultural, urban, and industrial) presents one of the major challenges facing water resources planners and managers. This competition, which historically has focused on apportionment, now involves the quality of the water and a range of associated issues related to effluents and return flows from each sector. Such changes in the way competing water uses are evaluated have added to the difficulty of river-basin-scale problems. Water development objectives often conflict with environmental constraints and pose seemingly insurmountable obstacles to regional planning (Whipple 1996). The overarching planning goal has expanded to that of supplying enough water, of adequate quality, to serve multiple purposes while complying with explicit legal restrictions.

Several authors have emphasized the need to jointly consider quality as well as quantity issues as a prerequisite for holistic and effective water resources management (Costa and Loucks 1987; Arnold and Orlob 1989; Câmara et al. 1990; Strzepek and Chapra 1990). In this vein, Loftis et al. (1985) investigated simulation and optimization approaches to specifying reservoir operation strategies for a system of lakes considering both quality and quantity. Pingry et al. (1991) presented a decision-support system (DSS) that incorporated a deterministic gross water and salt balance model in exploring water supply and water treatment alternatives to minimize economic costs on the upper main stem of the Colorado River Basin. Dandy and Crawley (1992) modeled the operation of a multiple reservoir system to determine optimal water supply to Adelaide, Australia, with consideration of the effects of water salinity. A network optimization model for real-time operation of the water system in the Avra Rift Valley of Israel was described by Meherez et al. (1992). Economically optimal allocation from multiple sources with varying salinity was made to a number of demands with varying quantity and salinity requirements. Hayes et al. (1998) addressed a problem in which daily reservoir releases were determined that produced maximum hydropower revenue while meeting downstream water quality objectives in the Cumberland River Basin. The scope of application in most of these studies was

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limited with respect to time period and spatial scale. In addition, only one of these studies linked reservoir releases to routing of streamflow and water quality (advective-dispersive transport) in downstream river reaches, and none considered parameter uncertainty. Indeed, despite this initial work, little has been accomplished in developing comprehensive approaches for integrated simulation of multiple water quantity and quality variables for strategic planning on a large scale (e.g., an entire river basin considering time periods of a decade or more).

Strategic river-basin planning is a feasibility-stage type of analysis that is used to identify ''broad brush'' alternatives that are promising for further consideration. Alternatives are developed and studied in sufficient detail to judge their relative merits in accordance with adopted criteria. More detailed and refined analysis is reserved for design and implementation phases wherein delineation of minor details and specification of composite elements within a strategy occur. Innovative and holistic approaches to strategic planning are required to manage riverine systems, characterized by complex objectives and relations among multiple and diverse water users, by numerous and varied feasible management alternatives, and by the far-ranging magnitude of the effects of management policies.

Described herein is the integration of water quantity and quality models, within a DSS framework, to support the difficult process of strategic river basin planning. A DSS is a computer-based advisory system for management that uses data bases, models, and communication/user-dialog facilities to provide decision makers with management information (Grigg 1996). The developed DSS addresses quantity and quality aspects as distinct, yet interrelated, subproblems. The methodology combines modified versions of two widely used models—a network flow allocation model (MODSIM) and a streamflow routing and water quality model (QUAL2E-UNCAS)—within a framework that allows basin-scale performance evaluation of strategic planning alternatives. The MODSIM model permits the user to establish priorities among various demands and between satisfying demands and maintaining target reservoir levels. This allows the model to easily simulate many potential operational scenarios. The resultant distribution of flows throughout the basin are then input into QUAL2E-UNCAS to simulate the corresponding water quality. The DSS allows easy formulation and evaluation of alternatives via a menu driven interface. The DSS is described in detail by de Azevedo (1994).

The study addresses space-time simulation of multiple reservoir operation, streamflow, and water quality in a river basin serving multiple economic sectors. It also incorporates analysis of parameter uncertainty. The study was motivated by and developed within the context of a planning problem for the complex Piracicaba River Basin in the state of Sao Paulo, Brazil. Decisions were needed regarding options for combination of flow augmentation and wastewater treatment designed to meet future water supply and water quality demands for the basin's growing municipal, industrial, and agricultural users. At the same time, regulatory standards for minimum streamflow, water quality, and a transbasin diversion southward to the city of Sao Paulo must be complied with.

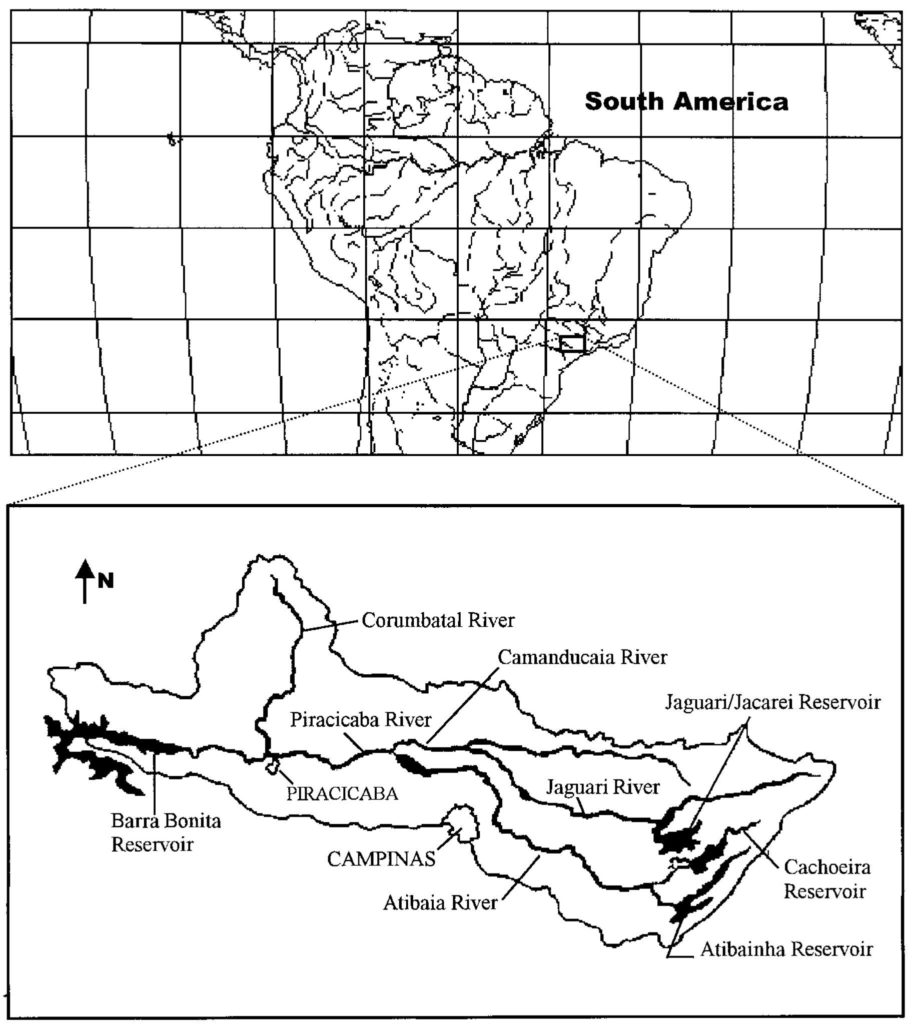

FIG. 1. Location of Piracicaba River Basin

PIRACICABA RIVER-BASIN PROBLEM

The Piracicaba River Basin is a large (12,400 km^2) and highly developed watershed located predominantly in the state of Sao Paulo, just north of the city of Sao Paulo, Brazil (Fig. 1). Three major tributaries—the Atibaia River, the Jaguari River, and the Corumbatai River—flow into the main stem (the Piracicaba River), which runs east to west. The mean annual flow of the Piracicaba River is about 140 m^3/s near the city of Piracicaba, just upstream of the confluence with the Corumbatai River.

With a population density of about 185 inhabitants per km^2, current urban water demands within the Piracicaba Basin amount to an average flow of about 4.1 m^3/s. The more than 200 industries (chemical, textile, alcohol, paper, etc.) in the basin divert about 20.4 m^3/s. About 6.1 m^3/s are needed to support crops (principally sugar cane) on about 14,000 ha of irrigated agricultural land. Urban, industrial, and agricultural water demands are projected to increase to 21.4, 30.3, and 10.9 m^3/s, respectively, by the year 2010. It is estimated that about 40% of these demands are consumptively used, with the remainder returning as point or nonpoint sources to basin streamflow.

Currently, only about 5% of the total organic load in urban return flows is extracted by treatment. The remaining 95% (about 76,000 kg BOD/day) is discharged into the river system. The industrial treatment level is currently at about 95% removal, with about 72,000 kg BOD/day of untreated waste discharged into the river system. If treatment levels are not improved, urban and industrial waste returns are expected to increase drastically to about 266,000 and 110,000 kg BOD/day, respectively, by the year 2010. Accurate estimates of pollution loads from agricultural effluents have not yet been made but are thought to be relatively small. Undoubtedly, this too will prove a concern as irrigated agriculture continues to expand.

About half of the water demand of the city of Sao Paulo is supplied by the Cantareira System of five reservoirs. Four of these reservoirs—the Jaguari, the Jacareí, the Cachoeira, and the Atibainha—lie in the headwaters of the Piracicaba Basin. Their physical characteristics are summarized in Table 1. The current legal demand for the transbasin diversion to the city of Sao Paulo is about 27 m^3/s, equivalent to more than 65% of the current total demand within the Piracicaba Basin.

The dilemma facing planners in the state of Sao Paulo is how to manage the limited water resources within the Piracicaba Basin to meet growing and competing demands for quantity and quality within urban, industrial, and agricultural sectors while maintaining satisfactory instream flows and water quality standards. Five water quality constituents of major interest are identified for consideration in the present study: DO, BOD, total nitrogen (N), total phosphorus (P), and fecal coliform (FC) as an indicator of pathogenic organisms. Current recommended instream standards for DO, BOD, and FC are >5 mg/L, <5 mg/L, and <1,000 FC per 100 mL, respectively, for the Piracicaba River Basin. Legal constraints on meeting transbasin diversion requirements to the city of Sao Paulo also must be considered. Before launching detailed economic and design studies, planners wanted to understand the overall technical feasibility of meeting basin-scale targets under broad classes of management alternatives. These classes would include (1) construction of new dams and reservoirs; (2) revision of release and storage patterns in existing reservoirs; and (3) increased levels of wastewater treatment.

TABLE 1. Physical Characteristics of Cantareira System Reservoirs

Reservoir (1)	Average inflow (m^3/s) (2)	Total storage (10^6 m^3) (3)	Active storage (10^6 m^3) (4)
Jaguari	20.6	134	95
Jacarei	3.8	917	713
Cachoeira	9.1	115	74
Atibainha	6.1	301	104
Paiva Castro	4.4	36	10

ELEMENTS OF STRATEGIC PLANNING MODEL

Planning Objectives and Performance Measures

Objectives for managing the water resources of the Piracicaba Basin relate to meeting the varying demands throughout the basin, maintaining satisfactory operational levels of water quality characteristics, and complying with water quality and in-stream flow regulations. To facilitate quantitative comparison among alternatives, several performance measures were adopted. Performance measures for meeting quantity objectives were total reliability, total vulnerability, and total resiliency of water supply. Water quality objectives were assessed using stream standard compliance reliability, water quality index, spatial uniformity of water quality, and temporal uniformity of water quality. All performance measures are consistently constructed to have values of 0–1, with 0 indicating undesirable performance and 1 indicating desirable performance.

Total Reliability of Water Supply

Burn et al. (1991) defined reliability of water supply as the probability that a reservoir system resides in a satisfactory state. For the Piracicaba Basin, a satisfactory state requires both of the following conditions: (1) Downstream demands must be fully satisfied (no shortages); and (2) reservoir levels must fall within 10% of target storage levels. Hence, the total reliability of the system is measured by

$$P_{rel} = \frac{1}{N_T} \sum_{t=1}^{N_T} Z_t \quad (1)$$

where N_T = total number of time steps within the operating period T (e.g., for monthly time steps over a 1-year operating period, $N_T = 12$); and the indicator function $Z_t = 1$ if the system (composed of all reservoirs) is in a satisfactory state for time step t and $Z_t = 0$, otherwise. Hence, P_{rel} ranges from 0 to 1, with higher values indicating higher reliability.

Total Vulnerability of Water Supply

Vulnerability in water supply usually is measured by the ratio of the amount of water delivered relative to the amount of water required (Djordjevic 1993). In this application, however, a surrogate measure of vulnerability was needed for the following reasons. First, the MODSIM model was set up to give a high priority for meeting water supply demands. Second, the time frame used in the analyses conducted in this study was 12 months. These issues will be discussed further in the section describing the water allocation simulation. As a result, for all alternatives analyzed in this study, the model always met the water supply demands by lowering the ending storage values as needed. The usual measure of vulnerability, as a ratio of deliveries to demand, would therefore equal 1 in all situations. To reflect the potential impact of reduced ending reservoir storage on the ability of the system to meet water supply in subsequent years, the surrogate measure of total vulnerability of water supply became the ratio of the total volume of water in storage at the end of the year relative to the target volume of carryover storage required

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$$P_v = \left(\sum_{R=1}^{N_R} V_{R,T}\right) \Big/ TV_{targ} \quad (2)$$

where $V_{R,T}$ = end-of-year storage at reservoir R; and TV_{targ} = target value of total end-of-year storage for the system. A very low value of P_v would imply that the system might be vulnerable in meeting water demands for subsequent years. This would also indicate that a longer period of analysis should be used. In this study, the minimum value of P_v was 0.70 indicating that a period of analysis of 12 months was acceptable.

Total Resiliency of Water Supply

Resiliency in water supply addresses how quickly a system returns to a satisfactory state after any reservoir in the system fails to meet demand or storage targets. During the simulation, each individual reservoir is checked to ensure that it meets its demand or storage targets. If at least one reservoir fails to meet its targets, then a system failure is considered to have occurred. Even if more than one reservoir fails, this is still considered as one system failure. The performance measure developed by Burn et al. (1991) was modified for use in this study. The measure of Burn et al. (1991) is

$$P_{res} = \frac{1}{\left[N_f\left(\dfrac{N_{cf}}{N_T}\right)\right]} \quad \text{for} \quad N_f \geq 1 \quad (3)$$

where N_f = total number of occurrences of system failure over T; and N_{cf} = the maximum number of consecutive periods of failure over T. In this form, P_{res} does not yield values over the interval of 0–1. However, dividing (3) by N_T and defining P_{res} when N_f equals zero yields

$$P_{res} = \begin{cases} \dfrac{1}{N_f N_{cf}} & \text{for} \quad N_f \geq 1 \\ 1 \quad \text{for} \quad N_f = 0 \end{cases} \quad (4)$$

Eq. (4) provides a performance measure that approaches 0 as the number of consecutive periods increases and equals 1 for either a single failure or no failures. Based upon the previous discussion of the vulnerability measure, it should be noted that the MODSIM model always met demands at the expense of achieving the storage target levels. Therefore, the performance measure of resiliency is measuring the characteristics of the failure patterns to meet within-year storage targets.

Stream Standard Compliance Reliability

To assure desired uses of available water resources throughout the basin, a planning objective is to maintain water quality that complies with all prescribed standards as often as possible. Hence, a performance measure of the amount of time when stream standards are not violated quantifies the degree of compliance at selected control locations considering the operating period of interest

$$P_{ssc} = \frac{1}{N_T}\sum_{t=1}^{N_T} Z_t^* \quad (5)$$

where the indicator function $Z_t^* = 1$, if the system is in a satisfactory state for time step t, and $Z_t^* = 0$, otherwise. A satisfactory state is defined as compliance with stream standards for all water quality variables of interest at all control points in the basin. Hence, P_{ssc} ranges from 0 to 1 with higher values indicating higher reliability.

Water Quality Index

The water quality index is a utility function that assigns a value indicating relative desirability to each collection of concentrations of the water quality variables. In the present study this performance measure is defined as follows:

$$P_{wqi} = \frac{1}{N_{cp}}\sum_{j=1}^{N_{cp}}\left[\frac{1}{N_T}\sum_{t=1}^{N_T} p_{wqi_{jt}}\right] \quad (6)$$

where

$$p_{wqi_{jt}} = \frac{1}{N_{qv}}\sum_{k=1}^{N_{qv}} C_{k_t} p_{wqi_{jtk}} \quad (7)$$

and N_{qv} = number of water quality variables; and $p_{wqi_{jtk}}$ = water quality index associated with the concentration C_{k_t}, of variable k at time step t, and at control location j over the N_{cp} water quality control points in the network. The functions $p_{wqi_{jtk}}$ are developed from surveys of expert opinion. For example, those developed for DO and P by experts in the state of Sao Paulo (de Azevedo 1994) are shown in Fig. 2. The values range between 0 and 1, with 0 indicating a completely undesirable state and 1 indicating a completely desirable state.

Spatial Uniformity of Water Quality

An important management objective is the equitable distribution of good water quality throughout the river basin. In the present study, equity was interpreted through spatial uniformity in the water quality index over the basin, as described in the following performance measure:

$$P_{suwq} = \begin{cases} 1 - \left[\dfrac{1}{N_T}\displaystyle\sum_{t=1}^{N_T} CV_{N_{cp}}(p_{wqi_{jt}})\right] & \text{if} \quad \left[\dfrac{1}{N_T}\displaystyle\sum_{t=1}^{N_T} CV_{N_{cp}}(p_{wqi_{jt}})\right] < 1 \\ 0, \text{ otherwise} \end{cases} \quad (8)$$

where $CV_{N_{cp}}(p_{wqi_{jt}})$ = coefficient of variation (the absolute value of the ratio of the standard deviation to the mean) over the N_{cp} water quality control points for time step t. For increasingly uniform conditions, the coefficient of variation will approach zero, and the value of P_{suwq} will approach the desired value of 1. If the situation is not uniform, then the coefficient of variation will increase, and for values of the coefficient of variation equal to 1 (or larger) the index will have a value of 0.

Temporal Uniformity of Water Quality

The objective of dependability in water quality at fixed locations within the river basin can be assessed through a performance measure for temporal uniformity

$$P_{tuwq} = \begin{cases} 1 - \left[\dfrac{1}{N_{cp}}\displaystyle\sum_{j=1}^{N_{cp}} CV_{N_T}(p_{wqi_{jt}})\right] & \text{if} \quad \left[\dfrac{1}{N_{cp}}\displaystyle\sum_{j=1}^{N_{cp}} CV_{N_T}(p_{wqi_{jt}})\right] < 1 \\ 0, \text{ otherwise} \end{cases} \quad (9)$$

where $CV_{N_T}(p_{wqi_{jt}})$ = coefficient of variation over the operating period N_T at the jth water quality control point. As for the case of spatial uniformity, for increasingly uniform conditions, the coefficient of variation will approach zero, and the value of P_{tuwq} will approach the desired value of 1. If the situation is not uniform, then the coefficient of variation will increase, and for values of the coefficient of variation equal to 1 (or larger) the index will have value of 0. The value of p_{tuwq} indicates the degree to which a certain level of average performance can be expected to occur over time in the basin. Even if the average performance is rather poor, information on dependability is useful in that it facilitates planning of operations that are needed to adapt to the expected performance level.

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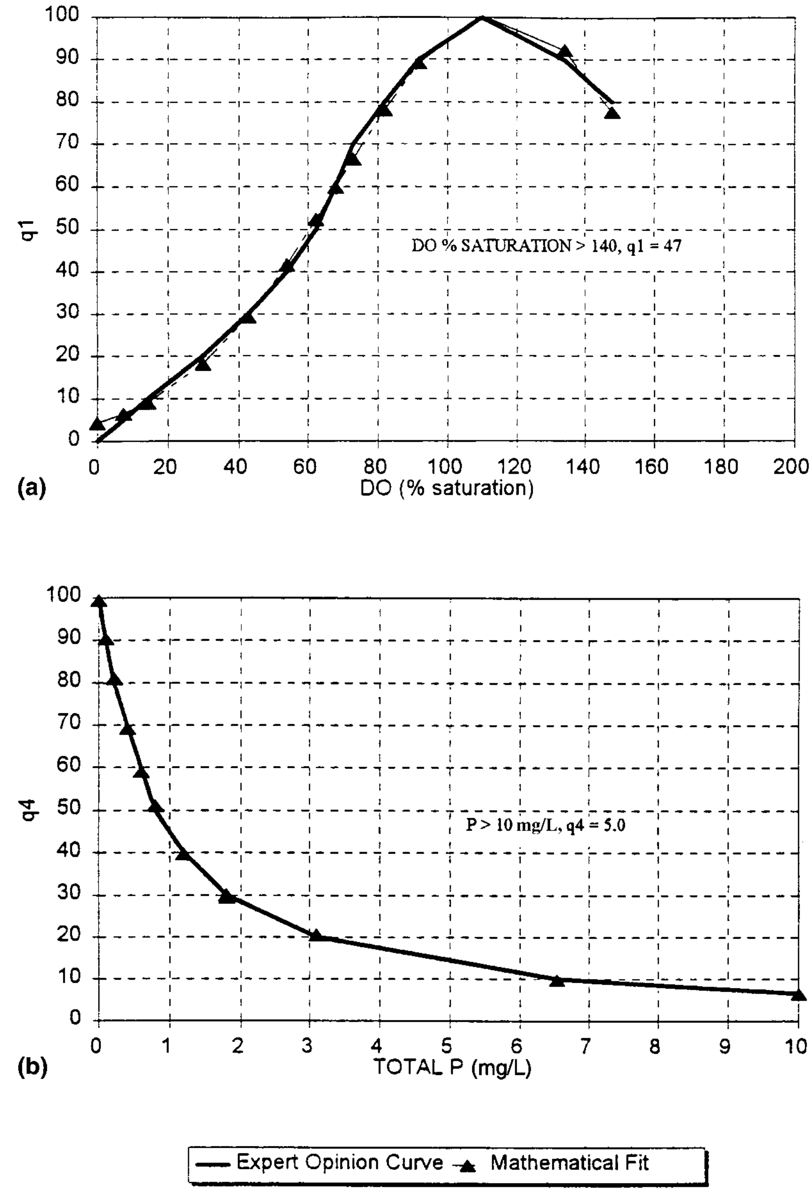

FIG. 2. Expert Opinion Curve for Water Quality Index Considering: (a) DO; (b) Phosphorus

Water Allocation Simulation Model

The water allocation component was developed around the river basin network flow accounting model, MODSIM (Labadie 1992). A major consideration in selecting a river basin simulation model is the ease and flexibility to specify various operational conditions. This includes the priorities of meeting the various demands and the desires to maintain target storage levels in the reservoirs. River basin simulation models specify the operational strategies by one of two methods: (1) Prespecified reservoir operational guidelines and rules for meeting downstream demands; or (2) using an embedded optimization model to meet the desired operational priorities. The MODSIM model uses this latter approach. It is a generalized river basin network simulation model that employs a state-of-the-art network optimization algorithm for each time period to assure that water is allocated according to physical, hydrological, and institutional aspects of river basin management. MODSIM has been used extensively for modeling water rights allocations in the United States. The advantage of MODSIM is that various operational scenarios easily can be simulated because only the priorities of meeting the various demands and reservoir target storage levels need be changed. This allows decision makers to rank the importance of competing water demands, including minimum in-stream flows.

In using MODSIM, the river system of the Piracicaba River Basin was represented as a network of nodes and links, illustrated schematically in Fig. 3. The nodes are representative of reservoirs, demands, control points, and river confluences. The links are connections between the nodes and are representative of river reaches or canal/pipeline conveyors. Three intrabasin reservoir nodes represent the Jaguari/Jacarei reservoirs (connected by a canal and operated as a unit), the Cachoeira reservoir, and the Atibainha reservoir. The other reservoir making up the Cantareira system, the Paiva Castro reservoir, is represented by an extrabasin node. Additional nodes, nine representing water quality control points within the basin, one representing the extrabasin demand node of the city of Sao Paulo, and one representing water imported to Sao Paulo from an additional source in Juqueri, also are included. Attributes assigned to reaches between nodes include hydraulic parameters, hydrochemical parameters, and distributed sinks/sources used

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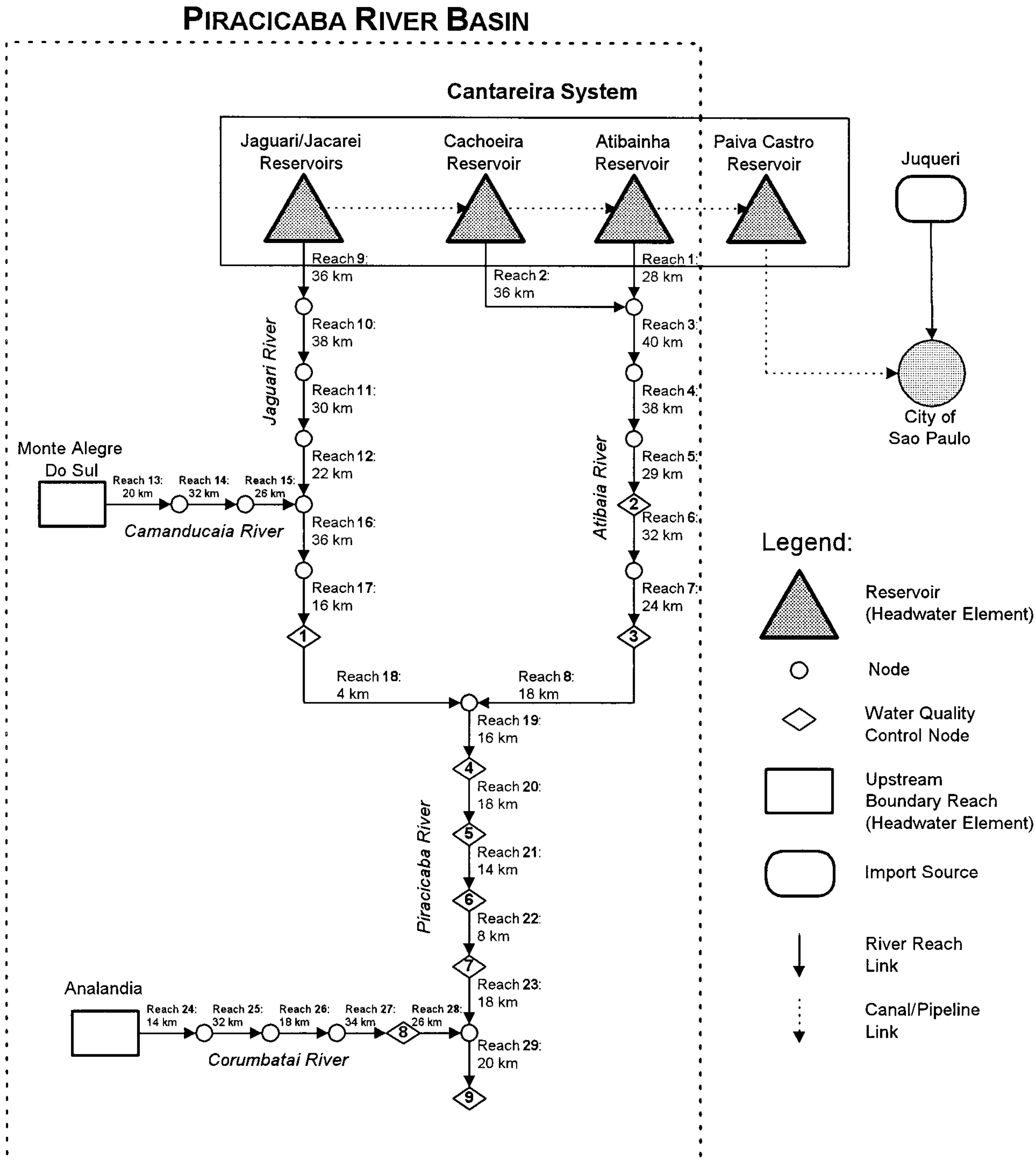

FIG. 3. Schematic of Piracicaba River Basin

in the linked QUAL2E-UNCAS model described subsequently. Not shown in Fig. 3 are the set of artificial nodes and links that are automatically created by MODSIM after formation of the physical network by the user. These artificial nodes and links are necessary for a fully circulating network structure whereby each node in the network is connected by both inflow and outflow links. Artificial links are created at each demand node, which terminate at a single artificial demand node. These links are assigned upper bounds corresponding to the demand at the node and (negative) link costs related to the priority ranking for that demand. Two artificial links originate at each reservoir and terminate at the artificial storage node, with one conveying carryover storage up to the target storage level in the reservoir, and the other carrying additional temporary flood storage above the target level. Bounds on the former links are the minimum and target storage capacities, with (negative) link costs defined according to the reservoir priority ranking. Capacities of the latter links are set at the flood space above the target storage level, with value of 0 assigned to carryover storage in these links because this is considered temporary storage capacity. Other artificial links and nodes are utilized in MODSIM, which are described in more detail in Fredericks et al. (1998), including explanation of the calculation of evaporation and other losses. Additional nodes are included in the network to facilitate the calibration process, to reproduce observed water transfers between reservoirs, and to achieve objectives related to releases for dilution flows (de Azevedo 1994). The sequential optimal alloca-

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tion problem is solved in MODSIM via the Lagrangian relaxation algorithm (Bertsekas 1991) in a sequential fashion over the modeled time period.

Water Quality Simulation Model

An expanded form of the QUAL2E-UNCAS model was used to simulate stream-water quality throughout the basin. QUAL2E-UNCAS is a version of the QUAL2E model (Brown and Barnwell 1987) that allows consideration of parameter uncertainty in predicting water quality variables. QUAL2E is the most widely used model for simulating stream-water quality in a planning context. The model can predict up to 15 water quality variables in branched stream networks assumed to be well-mixed both laterally and vertically. It performs a steady-state hydrological balance in terms of flow, a heat balance in terms of temperature, and a dissolved materials balance in terms of concentrations. The model uses a finite-difference formulation of the 1D advection-dispersion equations applied to successive stream reaches, each composed of a number of computational elements. Hydraulic and hydrochemical properties are assumed constant within each stream reach. Multiple waste discharges, withdrawals, tributary flow, and incremental inflow and outflow are allowed. Chemical reactions are handled through a variety of reaction kinetics equations (Chapra 1997).

The current version of QUAL2E-UNCAS was revised for use in the DSS. Prescribed levels of treatment can be applied to all contaminants, not just to BOD as in the original model. Also, the model dimensions were expanded to allow application to the Piracicaba Basin (Fig. 3): 29 river reaches composed of a total of 357 elements (each 2-km long), including 5 headwater elements, 4 junction elements, 48 inflow/withdrawal elements, and 12 stations at which statistics of the flow and quality variables could be calculated.

Reservoir releases determined by MODSIM become inputs (i.e., headwater boundary conditions) for the water quality model. QUAL2E-UNCAS is then used to route flows and to simulate concentrations of DO, BOD, N, P, and FC for successive time periods of interest. The results are evaluated in light of the planning objectives and performance measures, whereupon adjustments in reservoir operating targets and priorities are made in MODSIM followed by further evaluation by QUAL2E-UNCAS. This interactive process is repeated until satisfactory solutions are obtained, as described in a sequent section.

Incorporation of Parameter Uncertainty

Values of parameters describing hydraulic and physical properties, chemical properties, boundary conditions, and sink/source terms in a large river basin model are subject to substantial uncertainty. This uncertainty is derived from spatial and temporal variability, measurement error, and limited samples from the field. In the present problem, all parameters are treated as random variables, either normally or lognormally distributed in probability. Means and coefficients of variation for each of the parameters are derived from data collected in the field or from the literature, as summarized in de Azevedo (1994). Coefficients of variation ranged between about 0.05 to about 0.65. Inflows to each of the upstream reservoirs were modeled as multivariate autoregressive (lag of one month) periodic time series with statistical characteristics derived from historical flow records from the period 1940–1991. Given the lack of data for estimating correlation structure and given the rather coarse spacing (2-km distance between points along the river and time steps of 1 month) between parameter values in our planning model, statistical independence among hydraulic and water quality parameters was assumed. This approach is believed to allow a good estimate of the order of magnitude

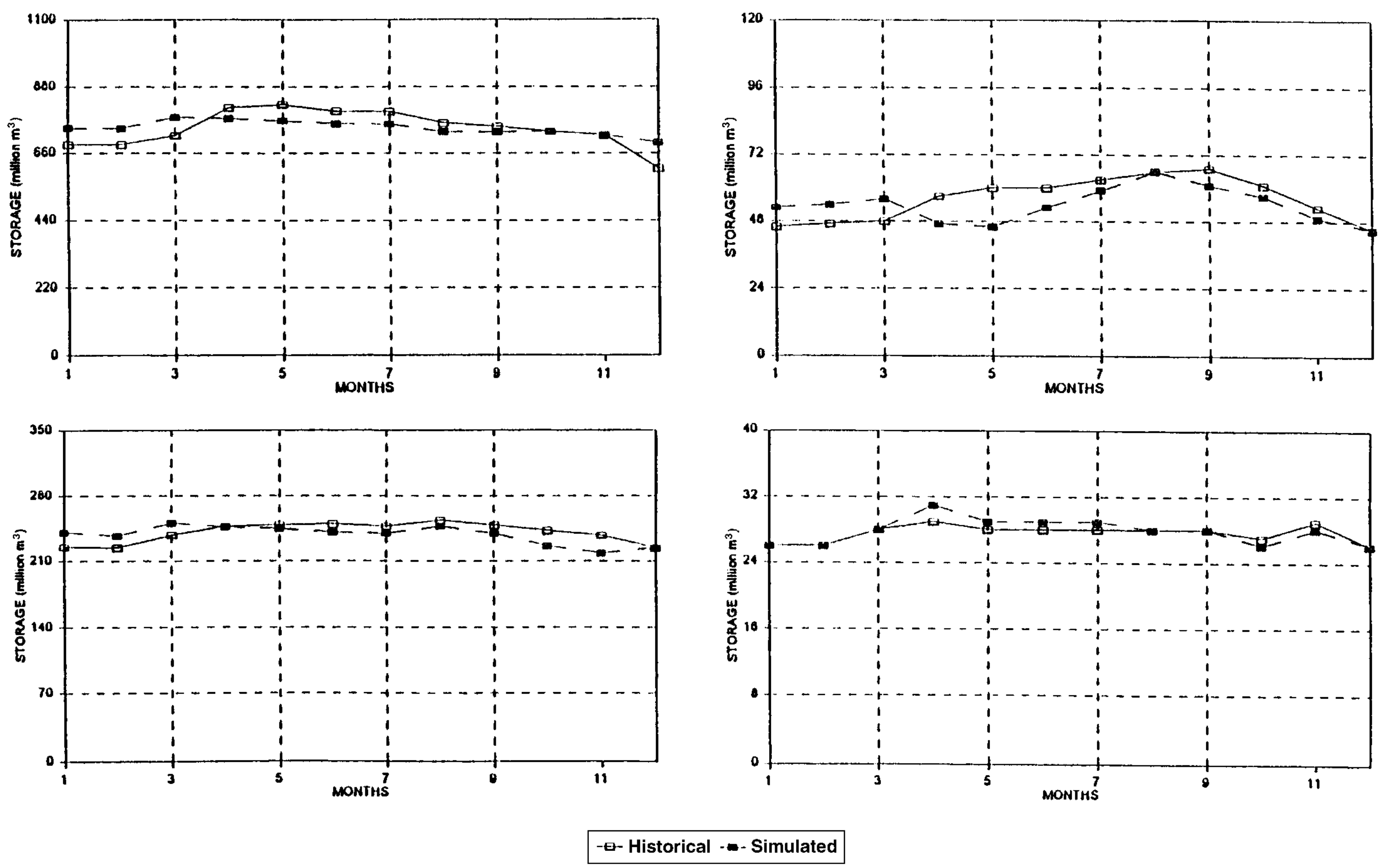

FIG. 4. 1990 MODSIM Calibration—Monthly Reservoir Storage: (a) Jaguari; (b) Cachoeira; (c) Atibainha; (d) Paiva Castro

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of uncertainty associated with predictions of system performance in strategic river basin planning. However, as more data become available, covariance structure should be included to refine the study, particularly at the design stage of analysis.

Stochastic simulation was accomplished through Monte Carlo generation of 250 possible realizations of collective parameter values for each planning alternative under consideration. Computational experiments revealed that 250 realizations were sufficient to achieve convergence of the statistics of the predicted flow and water quality variables and the associated performance measures within about $\pm 5\%$. Simulations were conducted using the parameter values from each realization as input to the planning model. Results then were analyzed to estimate statistics over the ensemble of 250 simulations for each of the computed performance measures.

For this study, the decision was made to limit the simulation period to 12 months and run multiple realizations of 12-month periods. The other option would have been to simulate a very long series of inflows to the system. It was computationally easier to run the QUAL2E-UNCAS model using the multiple realizations of 12-month periods. The validity of such an approach depends upon the ability of the system reservoirs to consistently refill. This was expected based upon the historical operation of the system, and this was demonstrated in the simulation results of this study.

APPLICATION AND RESULTS

Model Calibration

Both the MODSIM and QUAL2E-UNCAS components of the planning model were calibrated for application to the Piracicaba Basin by adjusting their configuration and parameters to ensure the ability to simulate historical data. In the case of MODSIM, historical records of monthly inflows, rainfall, reservoir releases, and reservoir storage for the years 1988 and 1990 were used for calibration. Historical observations of flows and concentrations of the five water quality variables at nine gauged locations in the basin over the period 1979–1991 were used to perform a calibration of QUAL2E for each of four quarters of the year for wet, dry, and average hydrological years.

In configuring MODSIM for calibration, the same high pri-

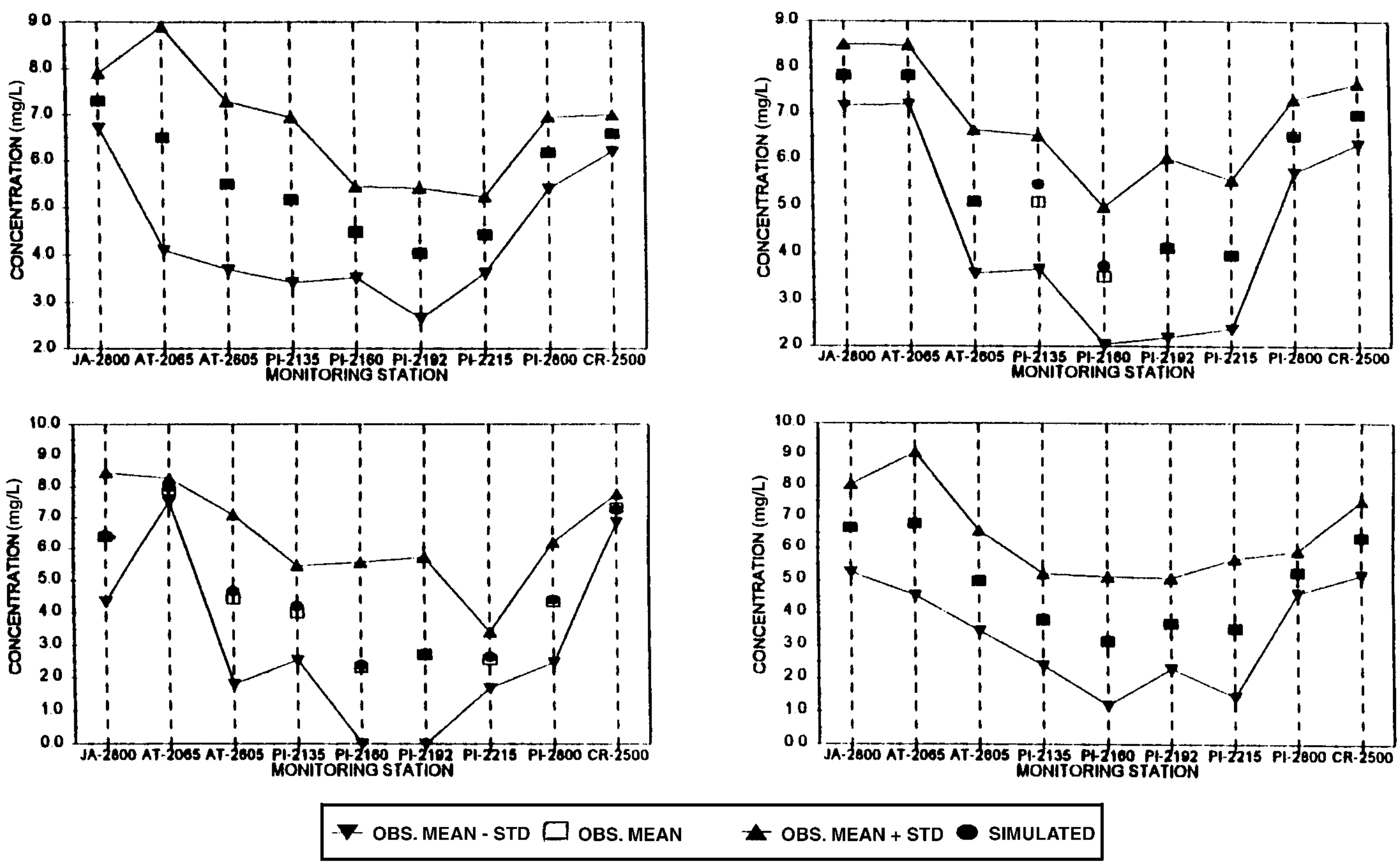

FIG. 5. QUAL2E Calibration—Piracicaba Watershed—DO: (a) First Quarter; (b) Second Quarter; (c) Third Quarter; (d) Fourth Quarter

TABLE 2. Statistics of Performance Measures Predicted for Alternative Strategic Plans Considered in Stage 1 for Current Demands and Average Hydrological Conditions

	P_{rel}		P_v		P_{res}		P_{ssc}		P_{wqi}		P_{suwq}		P_{tuwq}	
Alternative (1)	Mean (2)	*CV* (3)	Mean (4)	*CV* (5)	Mean (6)	*CV* (7)	Mean (8)	*CV* (9)	Mean (10)	*CV* (11)	Mean (12)	*CV* (13)	Mean (14)	*CV* (15)
E	0.68	0.28	0.79	0.23	0.19	1.46	0.00	—	0.70	0.03	0.88	0.011	0.94	0.008
R1	0.68	0.28	0.79	0.22	0.19	1.46	0.21	0.70	0.77	0.03	0.92	0.008	0.96	0.005
R2	0.71	0.28	0.85	0.20	0.25	1.03	0.00	—	0.70	0.03	0.89	0.011	0.94	0.008
R3	0.71	0.28	0.85	0.21	0.25	1.03	0.25	0.68	0.76	0.03	0.92	0.008	0.97	0.004
R4	0.71	0.28	0.87	0.22	0.25	1.03	0.61	0.53	0.81	0.02	0.93	0.008	0.97	0.004
R5	0.73	0.23	0.89	0.21	0.25	1.03	0.70	0.48	0.82	0.02	0.94	0.007	0.97	0.004

ority was used for every flow demand in the network, including the transbasin diversion to Sao Paulo, to ensure that all historical demands would be fully satisfied. A slightly lower priority was assigned to maintaining target storage levels in the reservoirs because mean daily storage in the historical database had to be transformed into average monthly values, a process that could yield small differences between observed and computed values. Results from the first calibration trial indicated that all downstream demands were fully met; however, some of the computed reservoir storage values deviated significantly from observed data. The cause was traced to an inappropriate transfer of flows between reservoirs in the network model. Hence, MODSIM was reconfigured by the placement of ''flow-through'' demand nodes between the reservoirs to force a reproduction of observed interreservoir transfers. A flow-through demand in MODSIM essentially provides a nonconsumptive demand on the level of flow in a reach according to a desired priority. A new trial run showed that this reconfiguration resulted in differences of <1% between calculated and observed values of downstream releases, water transfers between reservoirs, and transbasin diversions to Sao Paulo. Differences between calculated and observed reservoir storage, though larger, also were considered to be sufficiently small for strategic planning purposes, as indicated in Fig. 4 for the calibration year 1990. Final adjustments to model configuration were made to assure the capability of MODSIM to accurately simulate future management alternatives, including different values of intrabasin and transbasin demands, import of water from other basins, varying priorities in demand, extreme hydrologic conditions, and downstream water quality constraints. This required the introduction of additional flow-through demand nodes as described in de Azevedo (1994).

Mean values of the hydraulic, stoichiometric, and reaction rate coefficients for use in QUAL2E-UNCAS were estimated through a calibration process that accounted for seasonal and hydrological variations. Historical data on water quality concentrations for the five variables of interest were segregated into each of the four quarters of the year for each of three hydrological conditions. Wet, dry, and average years for a given quarter were those years in which average flows in the quarter exceeded about the 75% quantile, were below about the 25% quantile, and were between about the 25 and the 75% quantiles, respectively. The mean and standard deviation of the historic measured values of each of the five water quality variables of interest were estimated within each of the 12 groups. Calibration was accomplished by adjusting model parameters until calculated values of the variables and the corresponding flow rates fell between the observed mean value plus or minus one standard deviation and were closest to the mean for each of the nine control points. Example plots of simulated DO for the calibrated model at each of the control points are compared with statistics of observed data in Fig. 5. Plots for each of the four quarters of the year for average hydrological conditions are shown.

After calibration was completed, QUAL2E-UNCAS was validated by simulating 3 years of record: a dry year, an average year, and a wet year. The standard of error of estimate averaged over each quarter within the average year (1983) ranged from as low as about 10% for DO to as high as about 30% for P (de Azevedo 1994).

Assessment of Planning Alternatives

The DSS was applied in three stages to evaluate alternative strategic plans for management of the Piracicaba Basin. Alternatives were formulated in consultation with agencies in the state of Sao Paulo and were assessed by comparing statistics of predicted performance measures.

In stage 1, the existing strategy in the basin was evaluated along with five proposed revised strategies under existing demand conditions and utilizing existing Cantareira Reservoir System operational policy. The existing policy requires release of 27 m^3/s to Sao Paulo and minimum instream flows of 15 m^3/s at Paulinea in the Atibaia River and 40 m^3/s in the Piracicaba River at the city of Piracicaba. The six alternatives of stage 1 are briefly summarized as follows:

- Alternative E: This alternative defines the existing state of the system with no flow augmentation from new reservoirs and no increased wastewater-treatment levels. Re-

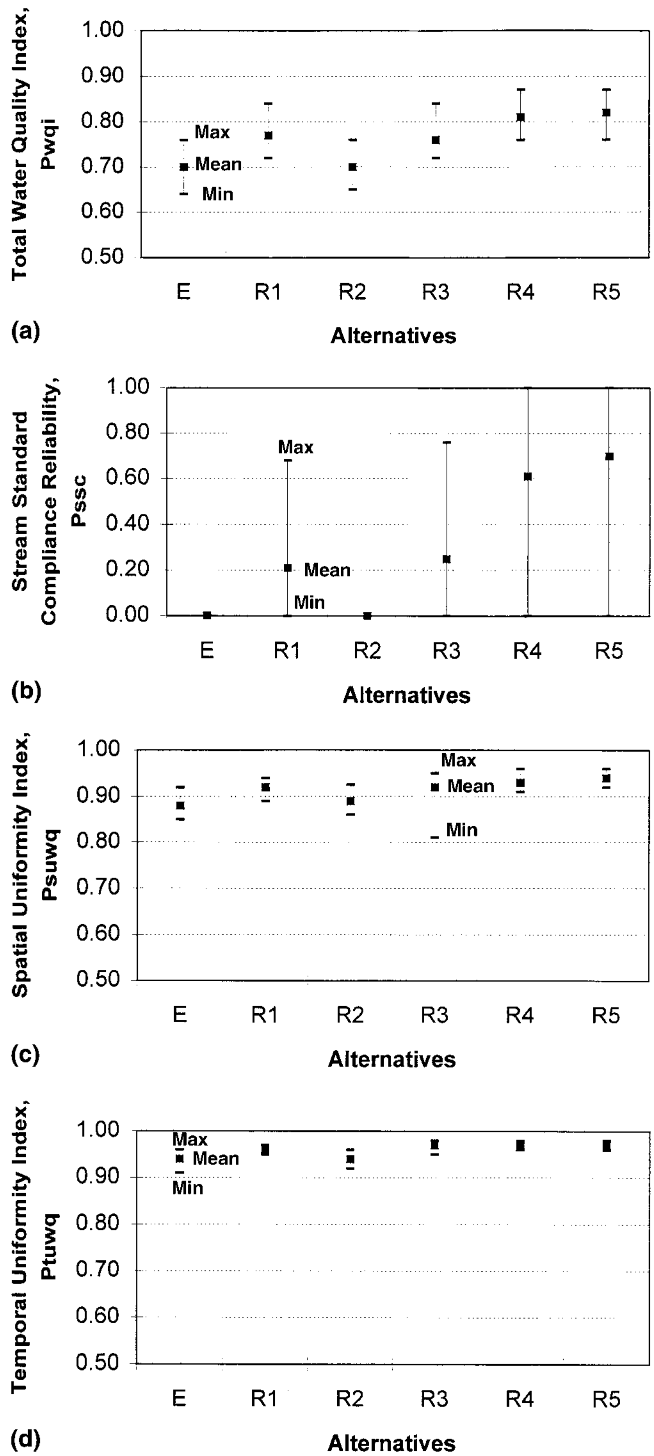

FIG. 6. Evaluation of Planning Alternatives: (a) Total Water Quality Index P_{wqi}; (b) Stream Standard Compliance Reliability P_{ssc}; (c) Spatial Uniformity of Water Quality P_{sumq}; (d) Temporal Uniformity of Water Quality P_{tuwq}

vision of release and storage patterns in existing reservoirs to best meet target demands was considered, however.

- Alternative R1: This revised alternative involves the increase of urban sewage treatment levels to provide 90% reduction of urban load at all discharge points within the basin. Revision of release and storage patterns in existing reservoirs was addressed, but flow augmentation from new reservoirs was not considered.
- Alternative R2: Construction of a dam near Monte Alegre, resulting in augmentation of 11 m^3/s of high quality water as the headwater boundary condition in the Camanducaia River, was considered in this option. Changes in wastewater-treatment levels were not considered, but revision of existing reservoir operation was included.
- Alternative R3: Alternatives R1 and R2 are combined to form this option.
- Alternative R4: This is an extension of alternative R3 to include an increase in industrial wastewater-treatment levels to 98% throughout the basin.
- Alternative R5: The characteristics of alternative R4 were included in this strategy along with an additional 6 m^3/s of flow augmentation. This flow would be provided by releases from a new dam constructed on a tributary to the Cachoeira River near its headwaters.

The analysis of alternatives considered in stage 1 was performed for monthly time steps over the 250 possible realizations of the model parameters, assuming average hydrological conditions. A statistical summary of the performance parameters predicted for each of the alternative strategies is presented in Table 2. The results show similar mean values of the water allocation performance parameters were predicted for all alternatives, with slightly better performance expected for the alternatives that include flow augmentation. Greater distinction between the planning strategies was revealed in the predicted water quality performance measures. Comparative range (maximum, mean, and minimum) plots for the alternatives are shown in Fig. 6 for each of the four water quality performance measures. Hence, alternatives R4 and R5 ranked highest in the analysis of stage 1. The CV values indicated low uncertainty in predicted values of P_{wqi}, P_{suwq}, and P_{tuwq} and higher uncertainty in predicted P_{ssc} (Table 2). The highest CV values over all of the performance measures occurred for P_{res}. This reflects the previously discussed situation of the MODSIM model sacrificing meeting reservoir storage targets to meet demand targets.

In stage 2, the two highest ranked revised strategies, alternatives R4 and R5, were compared to alternative E under future demand conditions estimated for the year 2010. The three alternatives were evaluated under average hydrological conditions and under the more restrictive case of dry hydrological conditions. The effect of a contemplated increased transbasin diversion requirement of 33 m^3/s to Sao Paulo was also considered. Finally, in this stage alternative R5 was studied under both the existing Cantareira Reservoir System operational policy and under a revised policy. The revised policy adjusted priorities in MODSIM to discourage excess water releases from the reservoirs during the winter months, to increase dry season reservoir storage, and to permit additional imported water to Sao Paulo from Juqueri.

The predicted performance for future water demands and average hydrological conditions are summarized in Table 3. Both water allocation performance and water quality performance were substantially greater for alternatives R4 and R5 compared to alternative E. Although predicted water quality performance measures were reasonably high, several problem regions were identified within the basin where performance was distinctly lower. Hence, for stage 3, an enhanced version of alternative R5 was considered.

Results from the stage 2 analysis also revealed that increasing the diversion to Sao Paulo would result in substantial reduction in the amount of water available for downstream users and excessive depletion of reservoir storage, mainly during dry years (de Azevedo 1994). For example, under existing operational policy, predicted mean values of P_{rel} for alternative R5 were 0.72 for 27-m^3/s transbasin diversion to Sao Paulo with average hydrological conditions, and 0.37 for 27-m^3/s diversion to Sao Paulo under dry hydrological conditions. For a 33-m^3/s required diversion to Sao Paulo, mean P_{rel} values were only 0.52 and 0.27 under average and dry hydrological conditions, respectively. Abandoning consideration of increased diversion to Sao Paulo, the performance of alternative R5 was analyzed for the revised operating policy for the Cantareira Reservoir System described previously. Predicted water allocation performance substantially increased from 0.72 to 0.97 for mean P_{rel} in average years and from 0.37 to 0.91 in dry years.

For stage 3, the final enhanced alternative, referred to as R5′, had the same characteristics as R5 under the revised Cantareira Reservoir System operating policy. In addition, alternative R5′ required secondary wastewater treatment at all waste disposal sites within reaches 6, 7, 18, 19, 20, and 22 in the network (Fig. 3), the regions where predicted performance was notably inferior under alternative R5. Secondary treated effluents usually contain very little BOD and suspended solids and may contain several milligrams per liter of DO. The pre-

TABLE 3. Statistics of Performance Measures Predicted for Alternative Strategic Plans Considered in Stage 2 for Future Water Demands

	P_{rel}		P_v		P_{res}		P_{ssc}		P_{wqi}		P_{suwq}		P_{tuwq}	
Alternative (1)	Mean (2)	CV (3)	Mean (4)	CV (5)	Mean (6)	CV (7)	Mean (8)	CV (9)	Mean (10)	CV (11)	Mean (12)	CV (13)	Mean (14)	CV (15)
E	0.51	0.53	0.70	0.26	0.04	0.47	0.00	—	0.60	0.04	0.85	0.014	0.92	0.010
R45	0.64	0.33	0.81	0.25	0.19	1.24	0.54	0.55	0.81	0.02	0.93	0.008	0.97	0.004
R5	0.70	0.30	0.82	0.24	0.19	1.17	0.66	0.50	0.81	0.02	0.93	0.009	0.97	0.004

TABLE 4. Statistics of Performance Measures Predicted for Alternative Strategic Plans Considered in Stage 3 for Future Water Demands, Average Hydrological Conditions, and Revised Operational Policy

	P_{rel}		P_v		P_{res}		P_{ssc}		P_{wqi}		P_{suwq}		P_{tuwq}	
Alternative (1)	Mean (2)	CV (3)	Mean (4)	CV (5)	Mean (6)	CV (7)	Mean (8)	CV (9)	Mean (10)	CV (11)	Mean (12)	CV (13)	Mean (14)	CV (15)
E	0.51	0.53	0.70	0.26	0.04	0.47	0.00	—	0.60	0.04	0.85	0.014	0.92	0.010
R5	0.74	0.24	0.86	0.22	0.86	0.34	0.66	0.50	0.81	0.02	0.93	0.008	0.97	0.004
R5′	0.74	0.23	0.87	0.22	0.86	0.34	0.82	0.005	0.82	0.02	0.95	0.005	0.97	0.003

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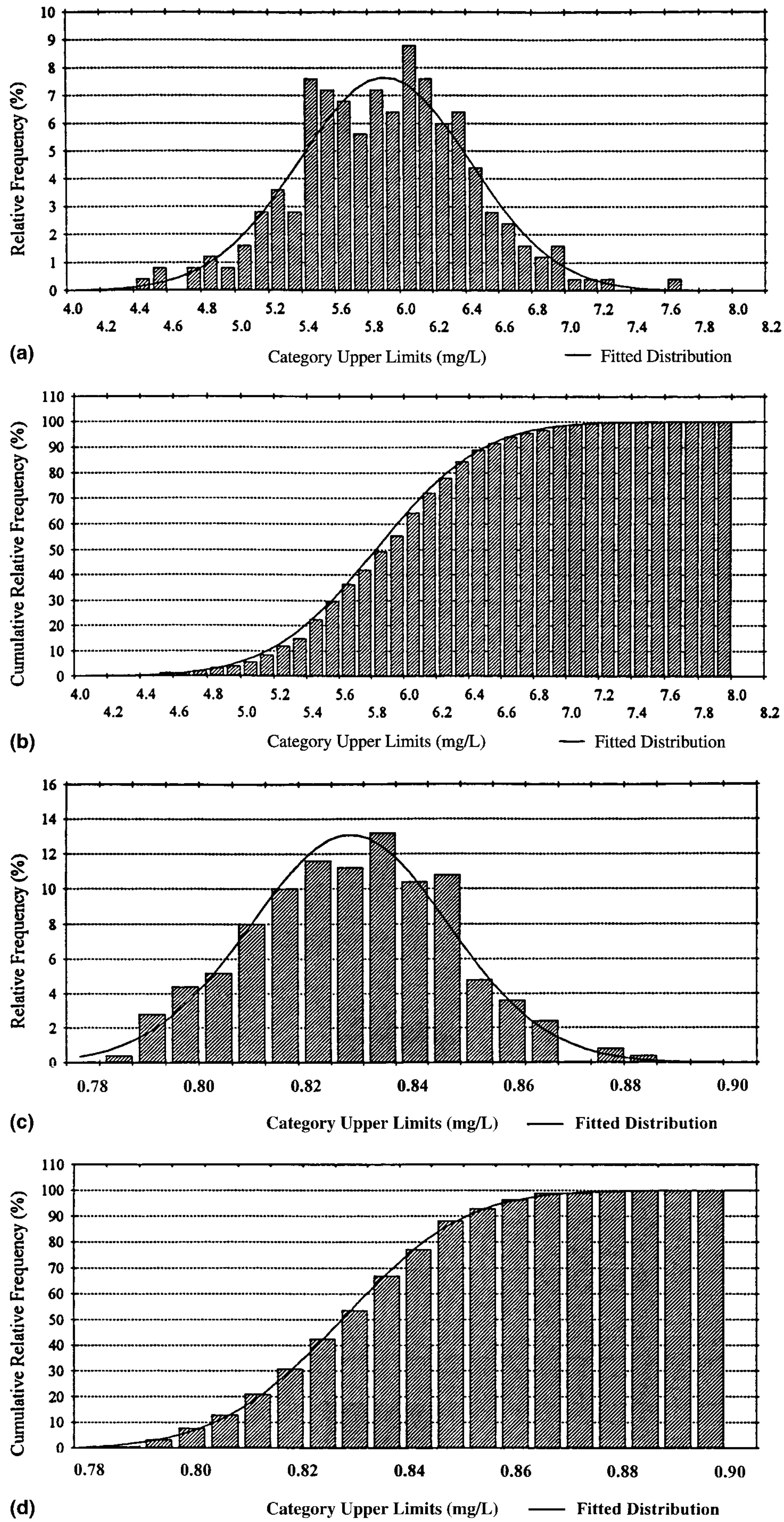

FIG. 7. Alternative R5′: (b) Example PDF of Mean DO Concentration; (b) Example CDF of Mean DO Concentration; (c) Example PDF of Total Water Quality Index P_{wqi}; (d) Example CDF of Total Water Quality Index P_{wqi}

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dicted performance of alternative R5′ is compared in Table 4 with that of alternatives E and R5 for revised operational policy under future demand and average hydrologic conditions. Results indicate increasingly higher expected values of performance measures for the revised alternatives R5 and R5′ compared to the existing condition, alternative E; moreover, the risk associated with predicted performance diminishes, as indicated by lower CV values. Probabilities of exceedance or nonexceedance of specified values of water quality variables or performance measures can be estimated from the cumulative frequency distributions over the considered realizations. Example distributions are shown for DO and P_{wqi} in Fig. 7, corresponding to results from revised alternative R5′.

During the present analysis, socioeconomic factors were not considered as direct decision variables. It is clear that socioeconomic concerns are translated, to a certain extent, into the recommended standard for water quality variables as well as water discharge in predetermined locations in the watershed. However, as a strategic planning tool for decision makers, the DSS would ideally be coupled with an economic model capable of bringing into the analysis information regarding cost and economic benefit of proposed strategic planning alternatives.

Once an alternative or a group of alternatives is chosen by the decision maker, a detailed investigation is necessary to refine the analysis to the point of bringing the proposed plan to the engineering design stage. The most significant benefit of such a DSS is to provide decision makers with a viable, cost-effective, and quick means to assess a number of strategic solutions with the objective of reducing the ''decision space'' to a smaller range of alternatives upon which to perform a more detailed analysis.

SUMMARY AND CONCLUSIONS

Systematic simulation of large-scale strategic planning for management of water quantity and water quality was accomplished through an integrated combination of water quantity and quality models. The approach focuses on aiding decision makers in the complex and difficult task of assessing system responses to strategic planning alternatives. Uncertainties normally associated with model predictions of system behavior, resulting from temporal and spatial variability and inadequate data related to model parameters, are accounted for in the modeling framework. Performance criteria have been developed with the objective of translating model predictions into meaningful information. These measures transform system responses such as carryover storage, releases, discharge rate, and concentration of water quality constituents into indices that incorporate frequency, magnitude and variability of deviation from target objectives, allowing for comparison among planning alternatives. The range of performance criteria can also be utilized in evaluating to what extent a plan contributes to the attainment of particular management objectives.

The utilization of the DSS for the case study of the Piracicaba Watershed has shown that pathways for solution of the very complex problems in the basin require increased levels of wastewater treatment and flow augmentation to meet increasing water demands and to maintain the diversion to Sao Paulo. It has also been determined that differentiated effluent treatment plans are necessary in problem areas. More importantly, however, has been the demonstration that ''good'' water quality can be obtained in the basin and that those benefits can be distributed with a high degree of equity among different user groups. It has also been shown that the diversion to Sao Paulo can be sustained by increasing downstream water supplies. The development of those supplies may be achieved with the construction of new reservoirs as illustrated in the analysis. Other means of providing additional supplies are the development of programs to promote water conservation and water reuse. As water availability becomes more scarce, these measures are an effective means of augmenting supplies and improving water quality.

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APPENDIX II. NOTATION

The following symbols are used in this paper:

C_{k_t} = concentration of water quality variable k at time period t;
CV = coefficient of variation (absolute value of ratio of standard deviation to mean);
N = nitrogen;
N_{cf} = maximum number of consecutive periods of failure over T;
N_{cp} = number of water quality control points in network;
N_f = total number of occurrences of system failure over T;

N_{qv} = number of water quality variables;
N_T = total number of time steps within operating period;
P = phosphorus;
P_{rel} = index of total reliability of water supply;
P_{res} = index of total resiliency of water supply;
P_{ssc} = index of stream standard compliance reliability;
P_{sumq} = index of spatial uniformity of water quality;
P_{tuwq} = index of temporal uniformity of water quality;
P_v = index of total vulnerability of water supply;
P_{wqi} = water quality index;
T = length of operating period;
TV_{targ} = target value of total end-of-year storage for system;
$V_{R,T}$ = end of year storage at reservoir R; and
Z_t = indicator function with values of 0 or 1.

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